GENERAL RESULTS OF EXPERIMENTS ON FRICTION AT HIGH VELOCITIES MADE IN ORDER TO ASCERTAIN THE EFFECT OF BRAKES ON RAILWAY TRAINS

THE experiments were made on the Brighton Railway, with the assistance of Mr. George Westinghouse, with a special four-wheeled van constructed for the purpose; it was attached to an engine, and was run at various speeds, during which time various forces were measured by self-recording dynamometers. The principle of these dynamometers is that the force to be measured acts on a piston fitting in a cylinder full of water, and the pressure of the water is measured by a Richards indicator connected by a pipe to the cylinder; thus, as the drum of the indicator revolves, diagrams are obtained, giving the force acting on the piston. The advantages of this method are obvious, because the indicator can be placed at any convenient point and the inertia of the water tend to make the pencil keep a position corresponding to the mean force. A detailed description of the construction of the dynamometers has been given in the *Proceedings* of the Institution of Mechanical Engineers, but would occupy too much space in this *résumé* of the experiments.

Brake blocks were applied to both pairs of wheels, but the dynamometers were attached to one pair of wheels only. The greater number of experiments were made with this latter pair of wheels, the second pair being reserved for special experiments when the van was slipped from the engine.

The levers for bringing the brakes into operation were so arranged that the brake blocks were applied on both sides of each wheel, and the pressure was equally distributed between the four brake blocks, acting on the pair of wheels.

The dynamometers above mentioned registered (1) The pressure applied to force the brake blocks against the wheels. (2) The friction which took place between the brake blocks and the wheels, due to that pressure, measured by the effort made by the revolving wheel to cause the blocks to revolve. (3) The weight on the springs over the braked wheels at each moment during the experiment, which, added to the weight of the wheels, axles, and springs, gives the weight for calculating the adhesion. (4) The tractive force exerted by the draw-bar. (5) Two self-recording speed-indicators were used, designed by Mr. Westinghouse, one instrument being attached to each pair of wheels. This instrument has been repeatedly tested, and was used at the brake trials on the North British Railway and on the German State Railways. It consists of a small dynamometer made on the same principle as that just described; it measures the centrifugal force of two weights, which are made to revolve by a strap from a pulley on a shaft driven by friction-gear from the pair of wheels to which the brake was applied; a Richards indicator is used, as with the other dynamometers. As the centrifugal force varies as the square of the velocity, the speed is got by taking the square root of the ordinate at any point of the indicator diagram.

The diagrams from one speed indicator showed the speed of the pair of wheels to which the brake was applied, and therefore the velocity of the train at the moment of applying the brake and subsequently, provided there was no slipping. Any variation in the speed-diagram was due to the wheels slipping, and shows to what extent and in what way the brake acted to stop the wheels. The diagrams from the other speed indicator showed the speed of the unbraked wheels. A Bourdon gauge, with the face divided in such a way that the hand showed the speed in miles per hour, was attached, for convenience, to the Westinghouse speed-indicator. As a check upon these, two of Mr. Stroudley's speed-indicators were fixed side by side in the van; one attached to the axle belonging to the braked wheels, the other to the axle which was running free. These indicators do not record the speed.

The indicators were all placed on a table in the centre of the van, and their drums were made to revolve by the cords being wound up on pulleys on a shaft, which was turned at a uniform rate by a water clock. This clock merely consisted of a plunger sliding in a cylinder through a water-tight packing, and loaded with a heavy weight; it was wound up by connecting it with the accumulator which supplied the dynanometers, and at the beginning of each experiment a small cock was opened which allowed the water to run out and the weight to fall, thereby turning the indicators round at an ascertained uniform speed. Thus, while the ordinates of the diagrams taken from these several indicators show the various forces, the abscissæ show the time occupied in the experiments.

In most of the experiments the tyres were of steel, and the brake-blocks of cast iron. Some experiments were made with wrought iron blocks, but the results were not uniform or satisfactory.

Numerous diagrams were taken with this apparatus, but it will suffice here to give the general results arrived at.

It is convenient in looking at the question of railway-brakes to consider first, what is the operation of a brake?

A train through the adhesion of the wheels of the locomotive acting on the rails, slowly accumulates energy, and for each ton of weight in the train, the accumulated energy is equal to 120 foot-tons at 60 miles per hour, 53 foot-tons at 40 miles per hour, and 30 foot-tons at 20 miles per hour. Thus, for a train of fifteen vehicles, weighing 200 tons, the energy at 60 miles per hour is equal to 24,000 tons falling a distance of one foot.

After a train has attained the desired speed, the reasons for stopping it may be of two kinds: (1) at prearranged places for convenience; and (2) for the prevention of accidents or for mitigating the consequences if accidents are unavoidable.

To stop a train for the first reason requires but a limited amount of force, which may be applied in any crude manner.

For the prevention of accidents, however, there is required:—

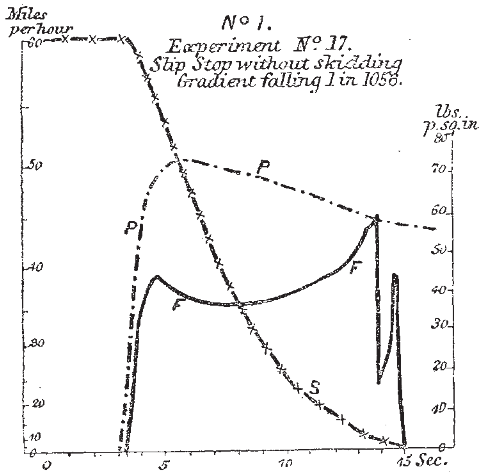
a. The instantaneous application of the greatest possible amount of retarding force.

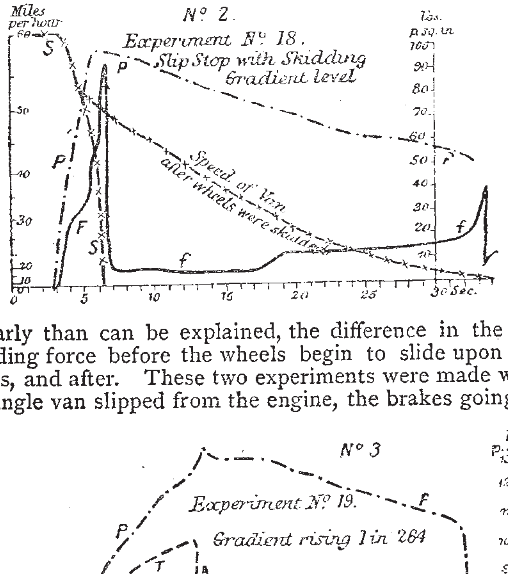
b. The continuous action of this force until the momentum of the train is destroyed.

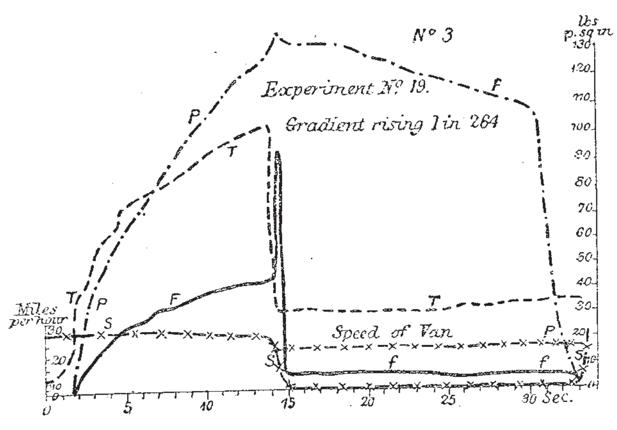
The retarding force used in practice is that due to the friction resulting from the forcible application of pieces of metals or wood (brake blocks) to the tyres of the wheels; this friction impedes the rotation of the wheels, and tends, through the adhesion of the wheels to the rails, to destroy the energy stored in the train. The retarding force is therefore limited to the resistance obtainable between the wheels and rails.

It was at first customary to attach to a train, for purposes of retardation, a certain number of vehicles with extra weight, to which the brakes were applied; but since the question of retardation has become better understood, brakes have been applied to every vehicle, the means of applying these brakes being placed in the hands of both the engine-driver and the guard. The reason for this is that the maximum amount of retarding force can be obtained only by applying brake blocks to every wheel in the train, each block being pressed with sufficient force to produce a resistance to the rotation of the wheel just equal to the greatest possible friction between the wheel and the rail. This greatest possible friction occurs when the adhesion of the wheel to the rail is just about to be overcome by the superior effort of the brake blocks, which effort, if further increased, immediately begins to stop the rotating movement of the wheel, and thus causes it to slide upon the rail. The experiments were made with the object of measuring the force thus brought into action.

The first result of the experiments was to show conclusively that the retarding effect of a wheel sliding upon a rail is much less than when braked with such a force as would just allow it to continue to revolve.





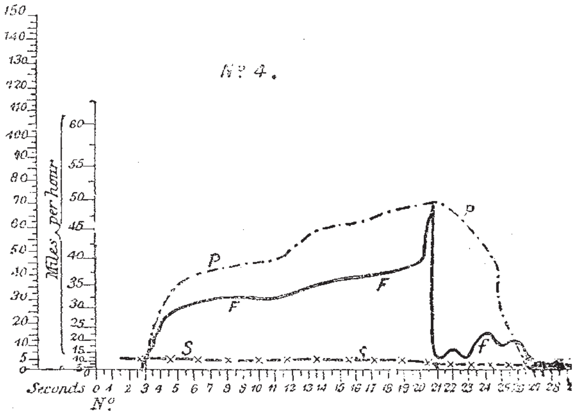


The annexed copies of two sets of diagrams (No. 1 and No. 2) taken during the experiments show, more clearly than can be explained, the difference in the retarding force before the wheels begin to slide upon the rails, and after. These two experiments were made with a single van slipped from the engine, the brakes going on automatically when separation from the engine took place. S is a line showing the speed of the van at each instant, the scale for which is at the left side. P is the pressure against four blocks acting upon one pair of wheels; the vertical height of P by the scale on the right hand multiplied by 240 gives the total pressure in pounds on the four blocks. F is the line showing the retarding effect of the four blocks upon the one pair of wheels before the wheels began to slide upon the rails; and *f* shows the effect while the wheels were sliding upon the rails. The vertical height of F or *f*, according to scale B, multiplied by 60, gives the retardation in pounds. It will be seen that the stop was made in half the time with the wheels braked but not skidded of that required when the wheels were skidded.

The accompanying Diagram 3 shows in another way the comparative retarding effect of the brakes when acting on the revolving wheels and when applied with sufficient force to skid the wheels.

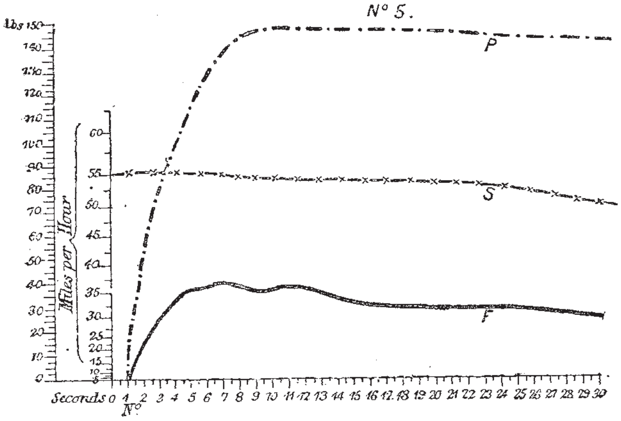
This experiment was made by keeping the van at a uniform speed on a rising gradient of 1 in 264—the line T shows the strain on the draw-bar during the experiment. The line S shows the speed of revolution of the braked wheels, when the revolution was checked and the friction diminished as shown by the line *f*; the strain, T, on the draw-bar diminished in a corresponding ratio.

From this it is evident that the retardation which arises when the wheel is sliding on the rail is far less than the retardation produced by the effect of the brake blocks when applied to the wheels so as to allow the wheels to continue revolving.



In order to understand this it is necessary to consider the general action of railway brakes. When a train is moving at a given velocity the adhesion of the wheels on the rails causes them to revolve; every point on the surface of the tyre moves round at the same rate as that at which the train itself is moving forward; but every such point in relation to the forward movement of the train comes successively to rest at the moment when it comes in contact with the rail. Now when the brake is applied with a slight pressure only, the wheel continues to move round at the same rate as that at which the train is moving, but it moves with more difficulty, and this increased difficulty in moving is shown either by an increase in the tractive force required to keep up the forward motion, or, in cases where the accelerating force is not kept up, by the tendency of the moving mass to come to rest in a shorter time than would otherwise be the case. But if the pressure with which the brake is applied be increased, a point is reached when the friction between the brake block and the wheel first approaches, then equals, and finally exceeds, the adhesion of the wheel on the rail. When this happens, the wheel first begins to revolve more slowly, and then ceases to revolve and slides along the rail, or, as it is usually termed, is skidded. The retardation is then no longer due to the friction between the brake block and the tyre of the wheel; but the vehicle is transformed for the time from a vehicle on wheels into a sledge, and the retardation is due to the excess of resistance which is produced by making the vehicle slide along the rails over that produced by making the vehicle move forward on wheels revolving freely.

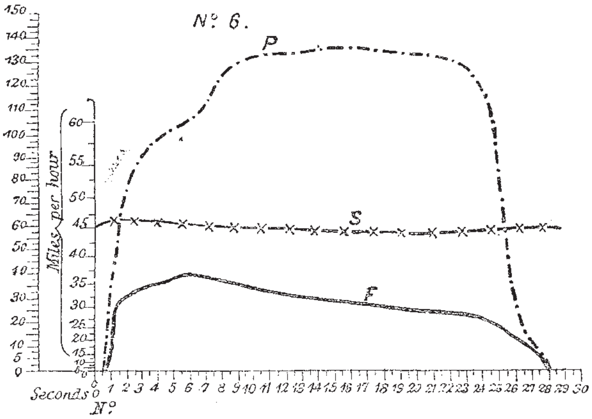
The reason why the retardation caused by the brake blocks applied to revolving wheels exceeds that caused by the skidded wheels became obvious from the fact next discovered, viz., that the coefficient of friction between the brake blocks and the wheels varied inversely according to the speed of the train, a higher proportionate percentage of brake-block pressure being required to obtain a given amount of friction at high speeds, and a lower pressure at lower speeds. This is illustrated by the Diagrams 4, 5. In these diagrams P represents pressure, F friction, and S speed, measured on the respective scales at the side to be corrected by the multiple before mentioned; it will be observed that the ratio of F to P in Diagram 4 with a speed of eleven miles per hour is much larger than that of F to P in Diagram 5 with a speed of fifty-five miles per hour.



The following table shows the coefficient of friction obtained from these experiments at varying speeds between cast-iron brake blocks and steel tyres:—

No. of experiments from which the mean is taken.	Velocity.		Coefficient of friction.		
	Miles per hour.	Feet per second.	Extremes observed.		Mean.
			max.	min.	
12	60	88	·123	·058	·074
67	55	81	·136	·060	·111
55	50	73	·153	·050	·116
77	45	66	·179	·083	·127
70	40	59	·194	·088	·140
80	35	51	·197	·087	·142
94	30	44	·196	·098	·164
70	25	36½	·205	·108	·166
69	20	29	·240	·133	·192
78	15	22	·280	·131	·223
54	10	14½	·281	·161	·242
28	7½	11	·325	·123	·244
20	Under 5	Under 7	·340	·156	·273
	Just moving		—	—	·330
Fleeming Jenkin		·0002 to ·0086	·337	·365	·351
Static friction (Rennie)					
180 lbs. per square inch	—		—		·300
336 lbs. per square inch	—		—		·347

If the position of the brake-blocks were always the same at the same speed, some simple rule might be deduced which would give the pressure required at each speed for obtaining a certain amount of retardation; but when the speed of the van was kept nearly uniform by the effort of the engine, the friction of the blocks decreased; and this occurred notwithstanding a continued increase of the brake-block pressure: showing that, through some cause not yet fully determined, the holding-power of brake-blocks at all speeds is considerably less after some seconds of application than when first applied. This peculiarity is illustrated by Diagram 6, and is also apparent in Diagram 5. Hence the question of the proper amount of brake-force needed at each instant, during the time required to stop a train, is still further complicated by this decrease which occurs in the coefficient of friction after the brakes have been applied, and which results from the time during which they are kept applied, irrespective of any change in speed. This decrease in the coefficient of friction is shown in the following table:—



Coefficient of Friction as affected by Time

Speed. Miles per hour.	Coefficient at commencement of experiment.	After 5 seconds.	After 10 seconds.	After 15 seconds.	After 20 seconds.
20	·182	·152	·133	·116	·099
27	·171	·130	·119	·081	·072
37	·152	·096	·083	·069	—
47	·132	·080	·070	—	—
60	·072	·063	·058	—	—

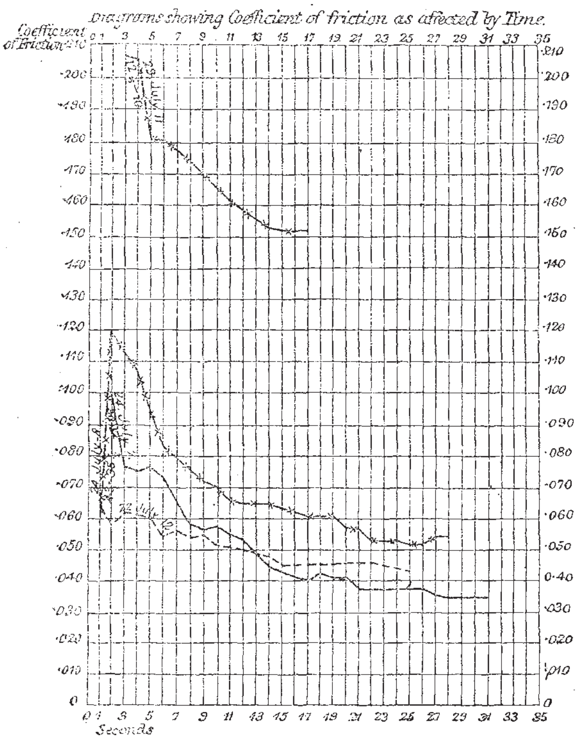
Diagram 7 shows the curves of this decrease obtained from a few of the experiments. It would seem as if the coefficient of friction due to each speed becomes nearly uniform after a certain number of seconds have elapsed. The experiments were, however, necessarily limited to something between twenty and thirty seconds each, so that this point has not been fully determined.

The decrease in the coefficient of friction, arising from time sometimes overcomes the increase in the coefficient of friction arising from a decrease in speed; especially when, either from the stop being on a descending gradient or from a small proportion of the train only being fitted with brake power, the train takes considerable time in coming to rest. Therefore, a higher brake pressure is required in such cases than when the stop is made in a short time.

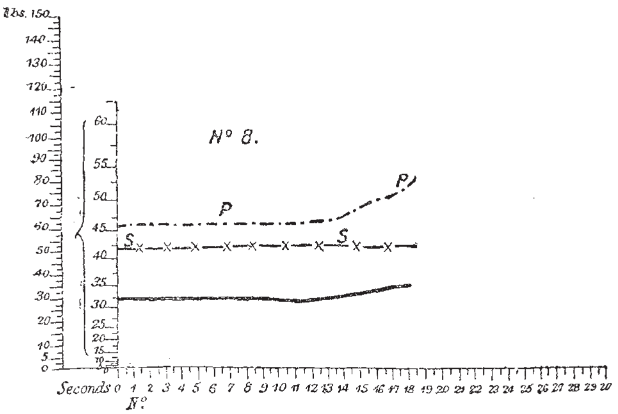
The accompanying diagram (8) shows a uniform force of friction with a practically uniform speed, as obtained by means of an increasing brake-block pressure. The line P, shows the pressure, F the friction, and S the speed, which decreased slightly during the experiment, and would have caused an increase in the coefficient of friction had it not been counteracted by the element of time.

There is nothing unnatural in the fact that friction decreases with speed. Friction is mechanical work; it requires a definite force to move a body which is in contact with another, and such movement causes a perceptible wear of the surfaces in contact. The manner in which this work is accomplished can be explained only by the fact that the surfaces in contact are not perfectly smooth, but irregular, although this irregularity may not be distinctly visible to the naked eye. These surfaces, if examined under a sufficiently strong microscope, would be found to be somewhat as represented in the accompanying diagram, No. 9.

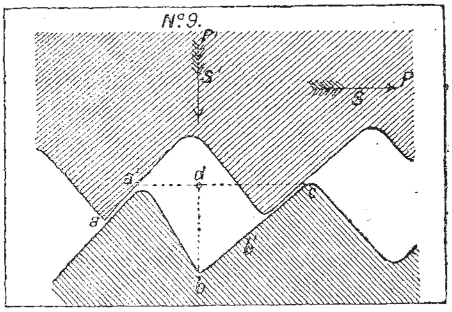
No. 7.



Diagrams showing Coefficient of friction as affected by Time.



If the upper body be moved in the direction of the arrow, S, by a force, P, the point, a, of the upper surface would mount the incline, formed by the corresponding portion of the lower body, until it reached its summit at a'; from this moment it would begin to descend the next incline, from a' to b; provided the force, P, acting in the direction of the arrow, S, would leave it time to do so, the incline from b to c would have to be mounted next, causing a certain amount of resistance during the time the body traversed the distance dc. But if we increase the speed in the direction of the dart S, so that the body will require less time to traverse $a'd$ than to fall through db, in such case a' would not arrive at c, but at some other point, b', and then only the portion of the incline $b'c$ would have to be mounted, presenting a smaller amount of resistance than in the former case. This illustrates what occurs.[1]



The fact that the coefficient of friction diminishes with speed sufficiently explains why a skidded wheel affords less resistance than one which still rotates, because the resistance occasioned by the rotating wheel is only limited by the adhesion of the wheel on the rail, and this, as already shown, is the same as static friction, since the point of the wheel is stationary as regards the forward movement of the train at the moment it touches the rail; whilst when the wheel is skidded and slides, the friction is that due to the speed at which the wheel moves on the rail, and is therefore less than the other.

DOUGLAS GALTON

(*To be continued.*)

GEOGRAPHICAL NOTES

ON Monday the French Geographical Society held an extraordinary meeting, in the large hall of the Sorbonne, for the reception of Major Serpa Pinto, the African explorer. We understand that Major Serpa Pinto and Lieut. Lucien N. B. Wyse have both promised to attend the coming meeting of the British Association at Sheffield, and will give accounts of their recent explorations in Africa and the American Isthmus. Some other very interesting papers, we hear, are in preparation for the geographical section, over which Mr. Clements R. Markham will preside.

THE principal novelty in this month's Petermann's *Mittheilungen* is an elaborate paper "On the Geographical Distribution of some Plague Epidemics," by Dr. Carl Martin. Dr. Emin Bey has a short paper "On the River Obstructions of the Bahr el Jebel," and we regret to say, Dr. Gerhard Rohlfs writes from Bengazi on June 10, that he has resigned the leadership of the expedition of the German African Society, which was organised for the purpose of reaching the Congo by starting from Tripoli. Dr. Rohlfs gives as his chief reason for resigning, the length of time the expedition is likely to last, and the value of even a single year at his age. He has, however, done his best to remove all difficulties from the way of the expedition in setting out, and these have not been few. He proposes Dr. Stecker to succeed him, and hopes the

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[1] This simple illustration is taken from an article in the *Chicago Railway Gazette*, by M. Krajewski.